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Report of
VLHC Instability Workshop
SLAC, March 21-23, 2001

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1 Introduction

The VLHC Instability Workshop was held at SLAC, March 21-23, 2001. The purpose is to review the instability issues facing VLHC, both for the high-field and the low-field stages. The review is considered a snapshot survey of these issues as presently conceived, and serves as input to its current Feasibility Study. The agenda is shown as Appendix. Presentations of the talks are posted on the web site http://www.slac.stanford.edu/ achao/VLHCworkshop.html.

In this workshop, we have agreed to use the following parameters as the nominal values (stage 2 values are at injection, unless otherwise specified):

	Stage 1	Stage 2
Circumference (km)	233	233
Revolution frequency (kHz)	1.29	1.29
Energy		
injection (TeV)	0.9	10
top (TeV)	20	87.5
Bunch spacing (m)	5.7	5.7
Number of bunches	37152	37152
Number of buckets	41280	41280
Protons/bunch (10^{10})	2.5	0.9
Beam current (mA)	190	69
Synch. rad. Power/beam (W/m)	0.03	5.6
Pipe/Liner		
aperture radius (mm)	9 x 14	10 x 10
material	1 mm aluminum	1 mm stainless steel
coating	-	50 micron copper
temperature (K)	300	80
Area coverage holes	-	4.0%
Lattice		
betatron tunes	218.3, 218.4	218.19, 212.18
slip factor	2.2×10^{-5}	2.65×10^{-5}
cell length (m)	271	271
beta average (m)	233	233
Rf frequency (MHz)	478	478
Rf voltage (MV)	50	50
90% long. Emittance (eV-s)	2.0	12.0
Trans. rms emittance (mm-mrad)	1.5	1.5
Rms bunch length (mm)	55	82
Rms energy spread σ_p/p	6×10^{-4}	2.3×10^{-4}
Synchrotron frequency f_s (Hz)	10.6	3.6
Synchrotron tune ν_s	0.0082	0.0028

In this report, we suggest that the following parameters be changed, or consider to be changed:

Stage 1 beam pipe radius and magnet gap

Stage 1 beam pipe thickness
Stage 2 liner thickness
Stage 2 liner coating thickness
Stage 2 liner temperature
Rf voltage
RMS long. emittance
We also suggest a list of R & D items.

2 Impedance Budget

Machine	R (m)	b (mm)	$Z_{\parallel}/n$ (Ω)	$Z_{\perp}^{BB}$ (MΩ/m) Broadband	Liner holes	$Z_{\perp}^{RW}$ (MΩ/m) Resistive wall
MI	529	25.4	1.6	2.2	-	26
LHC	4243	18.0	0.66	28	1.5	124
SSC	13866	16.5	0.68	54	21	4200
VLHC						
Stage 1	36924	9	0.6	490	-	65000 (?)
Stage 2	36924	10	0.6	390	90	55000

Table 1: Impedance budgets for various hadron rings. The resistive wall transverse impedance is quoted for the lowest frequency mode, at $(n - \nu_\beta)\omega_0$.

Scaling used:

$$\begin{aligned} Z_{\perp}(\text{broadband}) &\sim \frac{R}{b^2}(\text{rough}) \\ Z_{\perp}(\text{holes}) &\sim \frac{R}{b^3}(\text{exactforsamecoverage}) \\ Z_{\perp}(\text{resistive wall}) &\sim \frac{R^2}{b^3}(\text{one } R \text{ from 2-layer. Almost exact}) \end{aligned}$$

- Impedance per circular hole of diameter d:

$$Z_{\perp}(\text{holes}) = j\frac{Z_0}{24\pi^2}\frac{d^3}{b^4}$$

- Resistive wall impedance:

$$Z_{\perp}(\text{wall}) = \frac{Z_0 R}{b^3}\delta_s K \simeq \frac{Z_o R}{b^3}\frac{\delta_s^2}{\Delta}$$

where δ_s is the skin depth, Δ is the thickness of the copper layer, and K is the 2-layer multiplicative factor.

- Common parameters used here are

$$\begin{aligned}
\sigma_l(\mathrm{Cu}) &= 3.3\times10^9\ \Omega^{-1}\mathrm{m}^{-1}\ (\mathrm{RRR}=50,\ 30\ \text{for SSC}) \\
n-\nu_\beta &= 0.3\ (0.1\ \text{for SSC}) \\
\sigma_l(\mathrm{Al}) &= 0.056\times10^9\ \Omega^{-1}\mathrm{m}^{-1} \\
\text{hole coverage} &= 4\%
\end{aligned}$$

3 Transverse Mode Coupling Instability

The TMCI threshold for the resistive wall was calculated in Burov, et al "Beam stability issues in very large hadron collider". The formula for the threshold bunch population reads

$$\begin{aligned}
N_{\mathrm{th}} &= 1.24\times10^{10}\sqrt{\frac{\sigma_z}{10\,\mathrm{cm}}}\left(\frac{E}{3\,\mathrm{TeV}}\right)\left(\frac{\nu_s}{0.005}\right)\left(\frac{b}{0.9\,\mathrm{mm}}\right)^3\left(\frac{520\,\mathrm{km}}{C}\right) \\
&\times \left(\frac{250\,\mathrm{m}}{<\beta>}\right)\sqrt{\frac{\sigma_c}{3.5\times10^7/\Omega-\mathrm{m}}} \qquad (1)
\end{aligned}$$

Where σ_z is the rms longitudinal size, E is the energy, ν_s is the synchrotron tune, C is the circumference and $<\beta>$ is the average beta function. The simplified formulas in Bill Ng's estimation for the threshold give approximately a factor three larger threshold than in Eq.(1). The above number was obtained by a matrix approach for 25 modes (five radial and five azimuthal modes included) and by direct tracking. The difference between the matrix approach and particle tracking was about 30%. The main discrepancy between Eq.(1) and Ng's formula is related to the fact that the resistive wall wake goes to infinity as the inverse square root of the distance between particles and the wake, taken for a separation of the rms length of the bunch. Moreover, the infinite value of the wake for small distances brings up numerical convergence questions. It is worthwhile checking other approaches. V. Lebedev will perform independent particle tracking and M. Blaskiewicz will calculate the threshold using different expansions for the dipole moments of the beam. The problem is very important for the low field VLHC. The threshold number for the bunch population at injection with the nominal set of parameters (from the above formula) is equal to 1.142×10^{10} protons, about half the nominal intensity.

Thus the simplest estimation of the TMCI threshold yields numbers greater than the nominal bunch intensities. More precise calculations for the low field machine are based on scaling previous numerical calculations and solving the eigenvalue matrix, leading to a threshold of 1.14×10^{10} protons per bunch. So, the nominal intensity is twice the TMCI threshold in the low field machine. The estimate assumes a round beam pipe of 9 mm radius. The threshold estimate should be redone for the nominal oval-shaped beam pipe. The high-field machine TMCI threshold is of the same order.

Assuming that TMCI will exist in the VLHC, the following measures could be a cure:

- Inject low intensity bunches and coalesce them to make high intensity bunches at high field where the TMCI threshold is increased.
- Provide active feedback (resistive damping) at a few low order modes $\ell = \pm 1, \pm 2, \cdots$.
- Introduce an RF quadrupole to provide a tune shift between the head and tail of the bunch.

Some items for further study:

- The TMCI theory for proton beams is technically challenging because the bunches are longer and other forces may be present. Experimental data for comparison would be most useful.
- The TMCI can be studied with Tevatron Electron Lens (TEL).

4 Resistive Wall Effects

For the low field ring parameter range the various formulae for the resistive wall impedance agree within a factor of two. The e-folding time for the low frequency resistive wall instability is less than 1 turn. Additionally, the very low revolution frequency leads to a variation in the magnetic image Laslett tune shift when the ring is partially filled during the injection process. The variation is due to the fact that the revolution period is comparable to the magnetic diffusion time through the beam pipe.

Initial estimates of the latter effect produce tune shift variations of order 0.3 along the bunch train for a half filled ring. Both of these problems will be reduced by increasing the vacuum pipe thickness and/or radius. Increasing the dipole magnet gap from 20 mm to 28 mm reduces the DC Laslett tune shift from 1.0 to 0.6. The variation in tune along the bunch train could be reduced by quadrupoles running at multiples of the revolution frequency. Also, the resistive wall instability needs to be damped. Realistic studies of the feedback system are needed.

Uncertainties are larger for the high field ring and a reliable estimate of the transverse impedance is needed. Worst case estimates lead to resistive wall e-folding times of order 3 turns, significantly slower than in the low field case. Any damper technology required should easily follow from that developed for the low field case. Future studies may indicate that increasing the thickness of the copper layer is beneficial. The effect of dipole magnetic fields on the resistivity of the various materials should be understood.

5 Intrabeam Scattering

Intrabeam scattering is not a significant effect for Stage 1, because of the comparatively large beam emittance. For nominal parameters the amplitude growth rates are about 5 and 25 days for the horizontal and longitudinal degrees of freedom. At top energy, the transverse growth rate is about 22 days while the longitudinal rate stays approximately the same.

IBS is expected to be significant in Stage 2. The horizontal growth rate is by far the strongest, with growth times becoming comparable with the synchrotron radiation damping time when the vertical emittance shrinks to make the beam flat. The minimum growth time is controlled by heating in the longitudinal plane.

IBS growth rates calculated currently vary by as much as a factor of 4, depending on the model used. Better accuracy is needed.

6 Electron Cloud Instability

The electron cloud in the Stage 1 VLHC has started to be investigated. We ran the LBNL electron-cloud simulation code POSINST taking into account the actual beam parameters and an elliptic vacuum chamber design with uncoated aluminum (secondary electron yield at peak $\sim$2.75). We observe electron multiplication, as expected, since the nominal bunch spacing and current satisfy the multipacting condition. The power deposited at the wall by the electrons is 0.5 W/m in the dipole magnet section, in the worse case. The electron-cloud wake field is such that the vertical growth rate in the dipole sections is on the order of $t \gtrsim 0.25$ sec. The electron energy spectrum and the electron cloud dynamic have been also investigated. Thus, we have a preliminary understanding of the electron cloud issue in the Stage 1 VLHC, but more studies are necessary. Work in progress involves:

- complete the instability studies, looking at the electron-cloud wake field in other sections of the machine;
- study the head-tail instability;
- introduce the rediffused and the elastic components in the secondary electron energy spectrum.

The electron cloud instability does not seem a serious problem for stage 1. It will need to be studied for stage 2.

7 Impedance Reduction

It has long been realized that a large circular accelerator would have a large transverse impedance. The large circumference is a major factor, but the transverse size of the beam pipe is very important. The transverse beam size at high energies is very small - less than a few mm - and the imperative to design an affordable machine argues for a small aperture. The transverse impedance scales as $Z_\perp \propto C/b^3$, where C is the circumference and b is the transverse beam pipe dimension. This combination of effects increases the magnitudes of many coherent effects beyond what is normally encountered. It is critical to understand these phenomena in enough detail to determine whether the machine will produce the desired luminosity.

Given the large size of these effects, it is natural to consider methods that can be used to reduce impedance. The two main drivers, the circumference and transverse beam pipe size, are set by magnet technology and costs. We take these parameters to be fixed.

Cooling the beam pipe to cryogenic temperatures will result in a lower impedance for beam pipe materials (high purity copper and aluminum) although the effect is small for stainless steel. In addition to the cost of cooling the beam pipe, the synchroton radiation load should be considered in considering this option. The Stage 1 beam pipe is at 300 K, and the Stage 2 liner is at 80 K.

The thickness of the beam pipe can be increased. Assuming that the magnet gap were left constant, this would reduce the beam aperture slightly. For example, if the norminal wall thickness were increased from 1 mm to 2 mm, the aperture would decrease from 9 mm to 8 mm. However, transverse growth rates would decrease by about a factor of 2, and the dynamic Laslett tune shift would also decrease.

The concept for the high field machine beam pipe is a stainless steel pipe coated with copper. The nominal thickness of the liner coating is 50 μm. Increasing this thickness is desirable if possible.

Wake fields depend on the shape of the beam pipe. Asymmetric beam pipes may have some advantages, but this question needs to be studied in more detail, considering all coherent effects before making a specific recommendation.

There is a real need for an impedance estimate and budget for both the high field/low field rings. The impedance of the bellows has been estimated to be a major contribution to the broad-band impedance of the high field ring. Techniques of reducing the bellows impedance or of eliminating their impedance completely should be developed.

An idea for a super-beam pipe was presented. The super-beam pipe relies on a feed-forward system to create currents that cancel the wakefields caused by the beam currents. The concept should be studied further to understand more clearly the wakefield cancellation mechanism and the technical requirements. It would be fairly easy and inexpensive to perform bench tests of the concept.

8 Feedback Systems

It is generally agreed that at least two transverse feedback systems are required. The first is a high-gain, low bandwidth (perhaps 100 kHz) feedback system where the pickup signal arrives at the kicker slightly behind the beam bunch that produced the signal. The second is a conventional one turn delay system

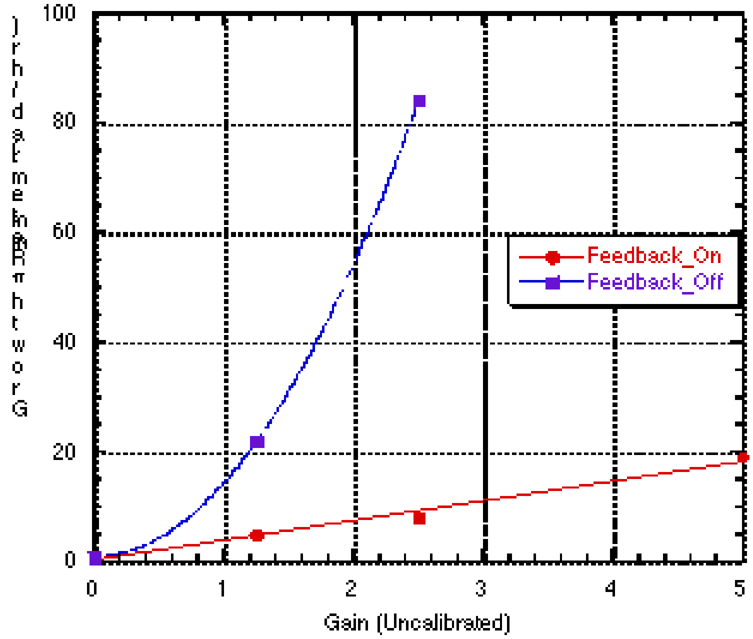

Figure 1: The power amplifier noise is applied to a beam in the Tevatron and the emittance growth is measured. The Feedback-On curve represents normal operation of the damper system and Feedback-Off is the same except that the feedback is turned off by unplugging the damper pickup signal. The damper feedback greatly suppressed the emittance growth caused by damper noise.

with a 26 MHz bandwidth. A high frequency system or perhaps a few systems may be useful to increase the TMCI threshold.

Low frequency, high gain transverse feedback A model was presented in which the single turn gain was limited to about 1 by unstable loop behaviour, independent of the number of systems used. The gain limitations need to be explored further to see if this limitation is fundamental.

The closed orbit correction and/or common mode suppression needs to be controlled at each pickup to the level of 100 μm. How this might be achieved is a method for future study. In particular, injection transients create special difficulty.

Damper emittance growth due to broad-band damper noise can be calculated as

$$\frac{d\epsilon}{dt} = 24\pi\beta_k f_0 \frac{Z_0 S^2 \ell^2 P}{g^2(E/e)^2}$$

where β_k is the beta function at the kicker, f_0 is the revolution frequency, Z_0 is the system impedance, S is the kicker sensitivity ($S < 1$), ℓ is the kicker

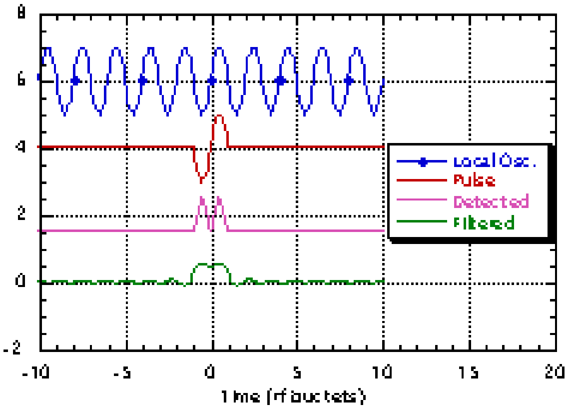

Figure 2: A cartoon of the TMCI pulse processing to develop a $l = \pm 1$ signal that can be digitized.

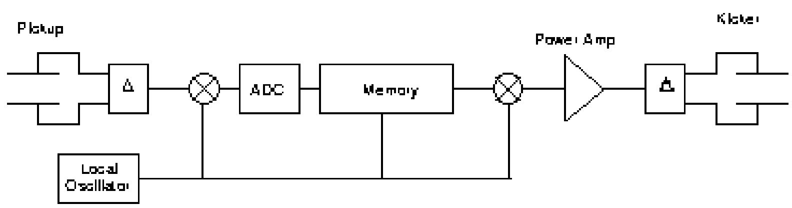

Figure 3: A damper schematic. The ADC and memory clock speed is equal to the bunch spacing (system requires a 27 MHz bandwidth for the VLHC).

length, P is the power input to the kicker, g is the kicker gap, and E/e is the beam energy. We conclude that the emittance growth for the VLHC feedback system will be small provided the noise can be held to the theoretical minimum "Johnson" noise.

The damper can suppress noise from other sources such as fluctuations in the magnetic field and ground motion. The following graph shows the suppression of emittance growth in the Tevatron damper.

Noise suppression in the strong damping regime should be studied in more detail.

One turn delay system The one-turn delay system is conventional in design and system gain and should not present any unusual difficulties.

TMCI System A concept for a TMCI damping system was presented. A mode $l = \pm 1$ signal is detected at a frequency appropriate for the bunch length. The signal is then mixed down to baseband and digitized by a conventional digitizer (one digitization per bunch). A rough idea of the signal processing and system block diagram are given in the figures.

Orbit, Tune, & Chromaticity Feedback Orbit feedback will be desired to control the damper system orbit to 100 μm. Global closed orbit may be useful in stabilizing machine behavior and reducing the time spent tuning the machine. It should also be possible to provide feedback for the tune and chromaticity.

9 VLLC, the e^+e^- Option

We heard a presentation on the VLLC, the e^+e^- option in the VLHC tunnel. This is a 184-GeV ring with a luminosity of 10^{32} cm^{-2} s^{-1}.We did not discuss in detail its instability issues due to time limitation, but noted the following:

- The high value of the beam-beam parameter, at 0.1, is an unfamiliar territory. Justification has been attributed to the exceptionally large radiation damping decrement.
- Lowering the RF Frequency from 400 MHz to 350 MHz should help to slightly relieve some of the instability considerations.
- TMCI at injection is identified to be by far the most dangerous instability mechanism if impedance is scaled from that of LEP (threshold current due to bellows alone is 10 times lower than design current). A combination of cures must be found. Possible cures include: (a) raising injection energy (perhaps to 45 GeV – the injector can then be used as a Z_0-factory); (b) a TMCI feedback system (see section on Feedback); (c) coalescing at top energy; (d) eliminating bellows; and (e) optimizing rf voltage, synchrotron tune, and momentum compaction factor.

10 R & D Items

The proposed low frequency feedback system is novel in that it operates at very high gain. A number of issues need to be considered.

- Can a stable feedback system be designed?
- Can a practical, low-noise design be implemented?
- How effective is the system at reducing noise from magnet ripple, ground motion, or other sources?
- Would a hardware test of the key concepts be possible?

The TMCI stability needs to be studied in more detail as well. Some of the key questions are

- Are there differences in behavior of proton and electron beams (either because proton beams typically operate in a different parameter range or because of the difference in mass)?

- Can the effect be excited with the Tevatron Electron Lens?

In addition, it would be valuable to directly measure the relevant tune shifts in the Tevatron, RHIC, and possibly other machines. If TMCI continues to be a problem at VLHC bunch intensities, cures should be considered including the use of an rf quadrupole to introduce a tune shift between the head and tail of the bunch and direct feedback on the higher order modes. Scenarios that finesse the instability (like bunch coalescing at higher energies, could also be considered.

Recent work decomposes the beam wakefield into deflecting and detuning wakes. The detuning wake depends on the shape of the beam pipe. The detuning wake should be studies to determine

- The theoretically optimum shape for the beam pipe
- Bench tests of new types of beam pipes

A concept for a "superpipe" was presented. The basic idea is to force currents through the beam pipe in a way that will compensate the beam wakefields. The idea should be further studied to understand what cancellation of wakefields could be achieved.

Additional topics for R&D are listed below

- Measure Intrabeam Scattering at RHIC (this will probably be done as a part of the RHIC program, anyway).
- Study feedback control of orbits, tunes, and chromaticity (LHC is working on this).
- Analyze the electron cloud instability (SPS is doing a lot of work on this subject, and a collaboration would seem to be desirable).
- Continue DB/B noise measurements in superconducting magnets.
- Study emittance growth in the Tevatron near integer tune. In this mode the Tevatron is sensitive to ground motion and other low frequency noise.
- Study in a parametric way instabilities in proton accelerators. There was some suspicion that instability thresholds were not as well understood in proton machines as they are in other machines and that existing theories are not well supported by experimental data.
- Study ways to eliminate the contribution of bellows to the impedance (either by better shielding or using fewer bellows).

Appendix

Agenda
VLHC Instability Workshop
SLAC, March 21-23, 2001

March 21, Wednesday
starting 9:00 a.m., ending 6:00 p.m.

- Business – Chao
- Overview – Blaskiewicz
- Beam instabilities in VLHC: from 1999 to now – Shiltsev
- Collective field effects: TMCI, tune shift, and emittance growth – Danilov
- Stability issues for the high field VLHC – Blaskiewicz
- Stability issues of the VLHC rings – Ng
- Workshop on an e^+e^- ring at VLHC – Wienands
- Vacuum system and synchrotron radiation – Pivi and Turner
- Longitudinal parameters – Marriner
- Feedback system requirements – Corlett
- No-host dinner at Capriccio's

March 22, Thursday
starting 9:00 a.m., ending 6:00 p.m.

- Control of transverse instabilities – Lebedev
- Formulation of issues to be addressed – Peggs
- Impedance budget – Chou
- Electron cloud in Stage 1 – Pivi
- Feedback against transverse coupled-bunch from resistive wall – Lambertson
- Approximate resistivity of thin wall – Lambertson
- Noise issues – Marriner
- TMCI Damper issues – Marriner
- Intrabeam scattering – Lebedev
- TMCI calculations – Ng
- Writing assignments

March 23, Friday
starting 8:30 a.m., ending 1:00 p.m.

- R & D issues – Marriner
- Longitudinal head-tail instability – Ng
- Continued discussions
- Unfinished homework
- Writing
- Reports on written drafts